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Analysis of Freezing Thawing Cycles on Unconfined Compressive Strength of Expansive Soil

Mohmad Maaz M. Mansuri [1], Bhavita Dave[2], C.H. Solanki[3] and A. K. Desai[4]

[1] M. Tech Student, Civil Engineering Department, S. V. National Institute of Technology, Surat-395007. Email: maazmansuri@gmail.com

[2] Research Scholar, Civil Engineering Department, S. V. National Institute of Technology, Surat-395007. Email: davebhavitas@gmail.com

[3] Professor, Civil Engineering Department, S. V. National Institute of Technology, Surat-395007. Email: chs@amd.svnit.ac.in

[4] Professor, Civil Engineering Department, S. V. National Institute of Technology, Surat-395007. Email: akd@amd.svnit.ac.in

Abstract. A significant portion of the earth surface is subjected to arid and semi-arid climatic conditions as a result of which many soils encountered in engineering practice are classified as an unsaturated soil. An unsaturated soil exists between the ground surface and natural water table. The type of soil frequently undergoes wetting and drying process due to seasonal variations. Due to this process, expansive soil may undergo swelling- shrinkage process. Considering the similarity between wetting-drying and freezing-thawing process, this study was an attempt to analyse the effect of the freezing-thawing process on Unconfined Compressive Strength (UCS) of expansive soil. For the experimental study, samples were moulded to achieve full compaction and field compaction (100%, 95%, & 85% of Proctor density) for different degree of saturation (60%, 40%, & 20% of optimum moisture content). The moulded samples were passed through required no. of the freezing-thawing cycles (0, 1, 3, & 5 nos.) and then tested for their UCS respectively. Results showed the effect of the freezing-thawing cycles for different compaction energy on UCS of expansive soil. It was observed that the UCS value increases up to 3 cycles and then decreases for the full compaction for different degree of saturation. While for field compaction, the UCS value reduces with the increasing no of freezing-thawing cycles.

Keywords: Unconfined Compressive Strength, Partly saturated soil, Freezing-thawing cycle, Expansive Soil.

1 Introduction

1.1 Unsaturated soil

Generally, soil mechanics can be divided into two main domains: one deals with the saturated portion of the earth, which means soil dealing with that portion of the earth whose voids filled with water or any other fluids. That means it contains two-phase system Soil solids and water (or air or any other fluids). Other Domain deals with the unsaturated or partly saturated soil which has some voids filled with water and some voids filled with air that means it contains a three-phase system, i.e. soil solids, water and air. Due to more than one fluid phase, it results in a change in material behaviour. According to Fredlund and Raharjdo (2012), the unsaturated soil is generally neither in arid condition nor in a saturated state, but it has degree saturation of ranging from 0 to 100%. Unsaturated soils (i.e., water and air in the voids) form the largest category of soils which do not follow the behaviour of classical saturated soil mechanics (Fredlund et al. 2012). Almost 60% of land area on earth is an arid or semi-arid region so that these soils strata are not fully saturated (Fredlund et al. 2012). Moreover, conventional soil mechanics considers fully saturated soil condition for shear strength analysis as a worst-case condition, but there were some landslides happened while soils are unsaturated also (Bharat et al. 2017). As artificial fills or earthen dam after construction does not remain in the same condition in terms of saturation during its life period. So that we need to analyse the soil condition in an unsaturated state, it leads to the development of conventional soil mechanics. Theories developed for the saturated and dry condition cannot be applied directly for the unsaturated condition. Terzaghi came up with a concept contractile skin which is nothing but a thin layer of the air-water interface and suggested that the contractile skin might be in the order of 10-6 mm in thickness.

1.2 Unsaturated shear strength

The shear strength of soil, whether saturated or unsaturated, may be defined as the maximum internal resistance per unit area the soil is capable of sustaining along the failure plane under external or internal stress loading. The shear strength of unsaturated soil appeals to more research in geotechnical engineering and practice from the last few decades. The shear strength of unsaturated soil governs main parameters of geotechnical engineering such as bearing capacity, earth pressure, slope stability etc. The shear strength of unsat. clayey soil is strongly influenced by the physicochemical interaction between water and clay minerals. Therefore, it is necessary to study the shear strength behaviour of unsaturated clayey soil.

Numerous experimental programs were conducted by various researchers to understand the shear strength behaviour of unsaturated soils from different countries. The series of six undrained and unconfined compression tests were conducted on unsaturated compacted clayey soil comprising 52% sand, 18% silt and 30% clay. [3] Guadalix Red silty clay was investigated by performing the test under net normal stress of 120 to 600 kPa for suction lower than the air entry value and obtained elliptical failure envelope. [8] The effect of suction on shear strength was studied by testing the clayey soil from Ningxia Hui, China, with advanced triaxial test apparatus. The suction-controlled direct shear test was performed on unsaturated expansive clay and studied the stiffness of clay with suction. [22] The consolidated drained test with modified direct shear apparatus was performed for investigating the Regina clay and Glacial till (clayey till) respectively. [21] Most of the investigators studied the shear strength behaviour on various types of unsaturated soils and observed the non-linear behaviour of the strength envelope. But very few researchers studied the shear strength behaviour of unsaturated clayey soil in the Indian context.

1.3 Shear strength equation for unsaturated soils

For saturated soil, shear strength is commonly described by the M-C failure criterion.

$$\tau_f = c' + (\sigma - u_w) \times \tan \emptyset' \quad (1)$$

Where, τ_f is the shear stress on the failure plane at failure,
c' is the effective cohesion,
$(\sigma - u_w)$ is the effective normal stress on failure plane at failure, and
$\emptyset'$ is the effective angle of internal friction.

Unlike saturated soils, the mechanical behaviour of unsaturated. soils depend on two independent stress-state variables. These variables are the stress tensor, (σ - u), which is net normal stress, and matric suction $(u_a - u_w)$ (Fredlnd & Rahardjo 1993). Soil behaviour is independent of the individual values of u_a, u_w or the total stress (σ) so long as the stress-state variables, $(\sigma — u_a)$ and $(u_a — u_w)$ are invariant.

Extended M-C failure envelope

Fredlund et al. (1978) proposed the equation which is shown below for determining the shear strength of partly-saturated soils in terms of two independent stress-state variables, $(\sigma_s — u_a)$ and $(u_a – u_w)$

$$\tau_f = c' + (\sigma_s - u_a) \tan \emptyset' + (u_a - u_w)_f \tan \emptyset_b \quad (2)$$

Where, τ_f is the shear stress on the failure plane at failure,
c' is the effective cohesion, which is the intercept of the extended M-C failure envelope on the shear stress axis where the net normal stress and the matric suction $((u_a - u_w)_f)$ at failure are equal to zero,
$(\sigma_s - u_a)_f$ is the net normal stress state on the failure plane at failure,
u_{af} is the pore-air pressure on the failure plane at failure,
ø' is the angle of internal friction associated with the net normal stress state variable- $(\sigma_s - u_a)_f$,
$(u_a - u_w)_f$ is the matric suction on the failure plane at failure, and
$ø_b$ is the angle indicating the rate of increase in shear strength relative to the matric suction- $(u_a - u_w)_f$.

This eq^n (2) is an extension of the M-C shear strength eq^n for a saturated soil. For unsaturated soils, the shear strength envelope was initially given as a planar surface based on a limited set of data available at that time in the literature (Fredlund et al., 1978). Later experimental evidence by several investigators established that the shear strength for unsaturated soils is non-linear when tested over a broad range of suction (Gan et al., 1988; Escrio & Juca, 1989). The Fredlund et al. (1978) equation is valid for interpreting data for both linear and non-linear shear stress.

1.4 Freezing-Thawing of soil

Jammu and Kashmir is the coldest region in India. Indian meteorological department reports the temperature varies from -20℃ in winter to 35℃ in summer. F-T cycle causes frost action, which leads to frost heave and thaw weakening. The former is due to formation of ice crystal, ice lenses and later is due to melting of ice. Casagrande (1931) observed that ice segregation did not appear in soils containing less than 1% of grains smaller than 0.02 mm. Freezing can be of two types open and closed system. De Groot (1951) defined as open system as an exchange of matter, heat, work and energy with its surroundings. Jones (1987) defined open-system freezing for soil as the condition where pore water in excess of that available in the voids of the soil, is available to be moved to the surface of freezing to form segregated ice in frost susceptible soil. De Groot (1951) defined as closed system as an exchange of heat, work and energy but no matter. Jones (1987) defined closed system of soil as, beyond the originally present water in the voids of the soil, there is no source of water available, during the freezing process or near the zone of freezing, and the ice lenses may or may not form. In an open system, as the freezing front moves downward, water is drawn up from a free surface through the soil. This movement of water due to freezing level creates ice lenses in the soil. Closed System there is a redistribution of moisture to the freezing front occurs, and this movement causes a decrease in dry density and an increase in water content near the freezing front.

2 Present Study - Unconfined Compressive Strength Test for Partially Saturated Soil

Geotechnical engineers are aware that the matric suction holds the soil together in UC tests (Fredlund & Rahrdjo 1993). In conventional analyses, in the undrained shear strength, the independent contribution of matric suction is not consciously considered. The matric suction is the function of the change in pore water pressure and the in-situ pore-water pressure, resulting from the stress relief during sampling in unsaturated fine-grained soil (UFG). Due to this, the measured undrained shear strength must be interpreted considering the influence of matric suction. Vanapalli et al. (1999) proposed a technique to estimate φ_b with respect to matric suction using unconfined compression test results for unsaturated fine-grained soils assuming a planar shear strength envelope.

$$\tan \emptyset_b = \left[\frac{\sigma_1}{2}(\cos \emptyset' + \sin \emptyset' \times \tan \emptyset') - \left(\frac{\sigma_1}{2}\tan \emptyset' - c'(u_a - u_w)\right)\right] \tag{3}$$

The pore-air pressure can be assumed to be atmospheric, and the test results can be interpreted taking constant matric suction. Eq. can be used to determine the contribution of matric suction in practical applications towards undrained shear strength, φ_b, knowing the UCS, $\sigma_1/2$ and matric suction, $(u_a - u_w)$ of the soil along with the effective shear strength parameters, c' and φ'.

In this study, the main aim was to study the effect of freezing thawing cycles on UCS of partly saturated expansive soil as we know that partly saturated soil has three-phase system containing solid, liquid and gas phase. So, the effect of alternate freezing thawing and change in the degree of saturation greatly influences the shear strength of the soil. CH soil of South Gujarat region was used. UCS tests were performed on different combinations of dry density, degree of saturation and F-T cycles. The samples were prepared for the degree of saturation of 80%, 60%, 40%, and 20%. While the dry density was kept 100%, 95% and 85% of MDD. Graphs were plotted to analyse the results.

3 Testing Material

In this study, the soil was collected from Jahangirpura, Surat region. The soil is black cotton (BC) soil in its physical appearance. The soil is classified as CH soil as per IS: 1498-1970. It is first oven-dried for 24 hours. After that drying, crushing and sieving of the soil were done. Then to identify the classification of soil type and various basic properties of soil, basic tests were performed. Below are the basic properties of soil.

Table 1. Engineering Properties of Soil

Property of soil	Value
Specific Gravity	2.69
Grain size distribution	
Gravel content (>4.75 mm) (%)	0
Sand (0.075-4.75 mm) (%)	9.82 %
Coarse sand (2-4.75 mm) (%)	0.54%
Medium sand (0.425-2 mm) (%)	0.99%
Fine sand (0.075-0.425 mm) (%)	8.29%
Silt (0.002-0.075 mm) (%) & Clay (< 0.002 mm) (%)	90.18%
Liquid Limit (wL) (%)	63.25 %
Plastic Limit (wp) (%)	25.92%
Plasticity Index (Ip)	37.33%
Maximum Dry Density (kN/m3)	16.79 kN/m3
Optimum Moisture Content (%)	16.571%
Indian standards classification - IS 1498 - 1970	CH

4 Experimental Setup

An UCS mould of size 38mm as an internal diameter and height of 76 mm was used for the experimental study. Sample extractor was needed to extract the sample from the UCS mould safely. A chest freezer with the temperature control up to -25° C was used to run the freezing thawing cycles of soil specimens. UCS/Triaxial Testing apparatus used for testing the sample.

5 Sample Preparation

From the Engineering properties of soil (OMC, MDD, G) amount of water required and amount of soil needed for each set of Sr and DD (DD = 100%, 95%, 85% of MDD, Sr = 60%, 40%, 20%) was calculated. Then Required amount of soil and water was thoroughly mixed in a bowel. Then it was delivered into UCS mould having dia 38mm and height 76 mm.

Each sample was passed through required no of freezing-thawing cycles except the samples which were of zero cycle. Zero cycle samples were directly tested. Samples which were not of zero cycles were subjected to required numbers of freezing-thawing cycles in a closed system. After preparation of the sample, they were put in the airtight plastic container to obtain a closed system, so that no moisture can come in or go out to or from the system. Then for the freezing process, the container was kept in the refrigerator for 24 hours. Freezing was done below -23 °C.

After 24 hours of freezing, the container was kept in the dark place for thawing at an average temperature varying between 25 °C to 30 °C according to IS code 4332-4(1968) for 23 hours. Then container was put in equilibrium period for 1 hour. So, it took 48 hours to complete one cycle of freezing and thawing. Similarly, various cycles (i.e.0, 1, 3, and 5) were performed on a soil sample. For each combination (i.e. the same degree of saturation, same dry density, and same cycle) three specimens were prepared and tested. Then the average of those three readings was taken for the analysis. After completion of required no of cycles UCS Test were performed, and the shear strength of each sample was calculated from the results of the UCS test. After completing the UCS test on a different degree of saturation and various dry density for each cycle (0, 1, 3, and 5) analysis of the results were done. Graphs were plotted to know the effect of freezing and thawing cycles on the Unconfined Compressive Strength of the soil for the different degree of saturation and dry density.

As discussed earlier, in this study, for each density (i.e. 100%, 95%, 85% of MDD) taking degree of saturation from 100% Sr keeping an interval of 20%, i.e. degree of saturation varying from 100%, 80%, 60%, 40%, 20% were taken. But, due to having a more water content in 100% degree of saturation and 80% degree of saturation sample was very soft and had a negligible shear strength. So, it wasn't easy to perform the test.

Freezing thawing cycles were started from zero cycles keeping an interval of one cycle for the ease of analysis up to where curve shows reverse result i.e. in this study it was up to five cycles.

6 Results and Discussion

6.1 Comparison with the degree of saturation

UCS value vs No of Freezing-Thawing Cycles

UCS value (kN/m2) vs no of freezing-thawing cycles graphs were plotted to analyse the variation of UCS value with respect to no of F-T cycles. Comparison of UCS value with the degree of saturation was also plotted.

Dry Density = 100%

Table 2. Values of q_u for MDD-!00%

q_u (kN/m^2)				
Sr\ Cycles	0	1	3	5
60%	133.271694	201.3949	248.7607533	222.9693953
40%	474.2798647	491.801	578.295202	530.04673
20%	592.7762813	622.7191	708.1999633	307.044646

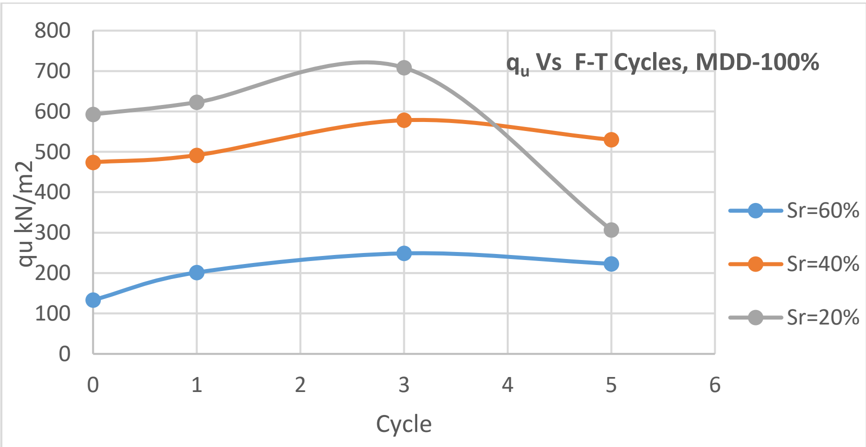

Fig.1. q_u vs F-T Cycles for MDD -100%

UCS value increased up to 3 cycles then decreased for 100% dry density for 60%, 40% and 20% degree of saturation.

Dry Density = 95%

Table 3. Values of q_u for MDD-95%

q_u (KN/m2)				
Sr\ Cycles	0	1	3	5
60%	27.52386	38.80145	341.9235	0
40%	365.1324	464.2771	460.5506	82.7677
20%	1034.106	1182.349	807.2793	219.8967

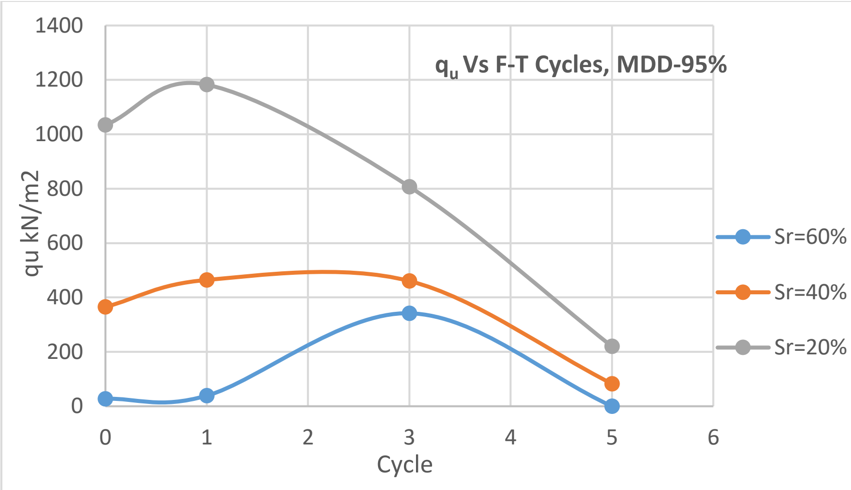

Fig. 1. q_u vs F-T Cycles for MDD-95%

UCS value increased up to 1 cycle then decreased for 95% dry density for 40% and 20% while for 60% degree of saturation, it increased up to 3 cycles (sudden increase for three cycles) and no value for five cycles.

Dry Density = 85%

Table 4. Values of q_u for MDD-85%

q_u (KN/m2)				
Sr\ Cycles	0	1	3	5
60%	0	0	0	0
40%	209.0113	171.2232	66.68488	41.77612
20%	883.7054	567.5406	465.6501	424.3316

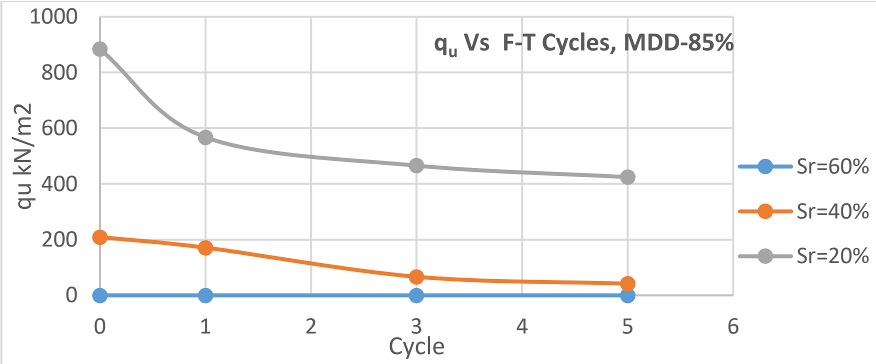

Fig. 2. q_u vs F-T Cycles for MDD-85%

UCS value decreased as the no of cycle increased for 85% dry density and 40% and 20% while for 60% degree of saturation it gives no value for all cycle as the sample becomes very soft.

Discussion from the above graphs (UCS vs F-T Cycles)

The freezing-thawing behaviour of an expansive soil at Proctor density somewhat varies with each other. It showed variation in UCS for F-T cycle for the individual degree of saturation. For 60% & 40% saturation, it increased up to three cycles and retarded for five cycles, whereas for 20% saturation it decreases as the nos of F-T cycle increases.

6.2 Comparison with Number of F-T Cycles

Dry Density = 100% MDD

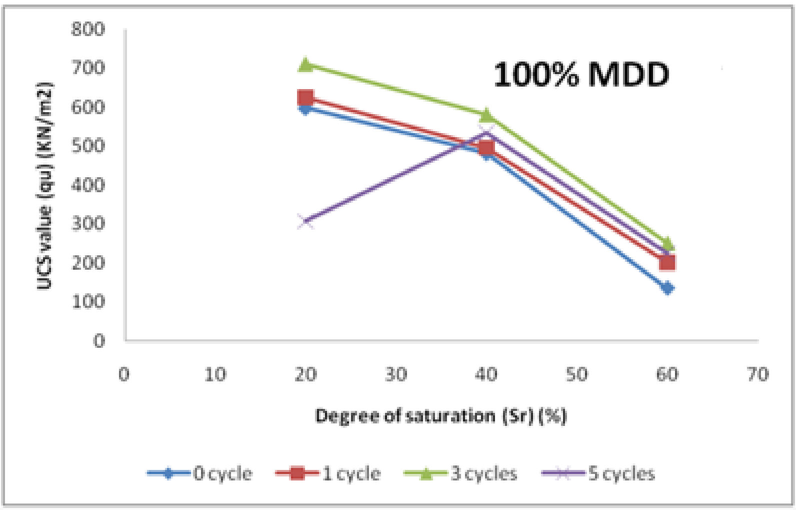

Fig. 3. q_u vs S_r, MDD-100%

Dry Density = 95% MDD

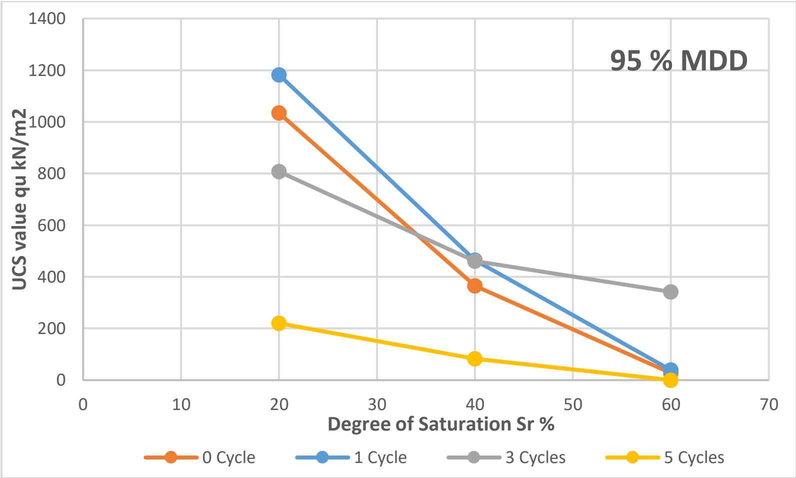

Fig. 4. q_u vs S_r, MDD-95%

Dry Density = 85% MDD

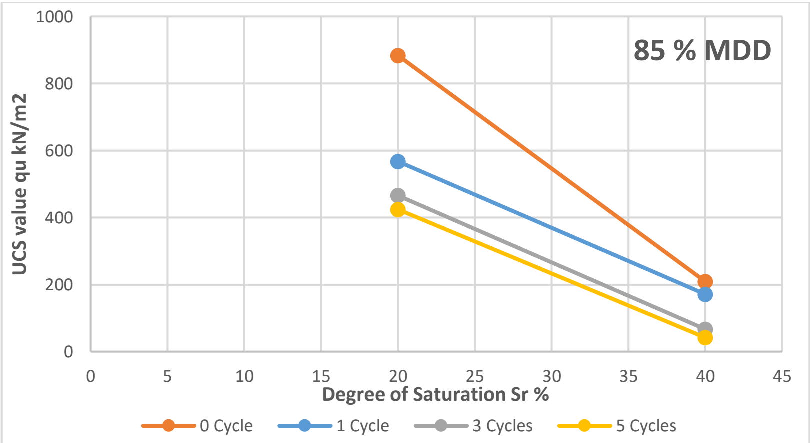

Fig. 5. q_u vs S_r, MDD-85%

The graphs show the continues retarders in UCS value with incremental of the degree of saturation for each FT cycle.

7 Conclusions

Through the analysis data of the experimental results, the following conclusions were obtained:

1. The UCS parameter in the freezing-thawing process (temperature variation) has been effective such as, the volume of voids effective on the shape of voids. Pores, neck and direction of water flow either getting in or out of pores which acted in the volume.
2. The UCS value has been increased up to freezing-thawing cycle (3 nos.), and then it reduces for 100% and 95% of Proctor density. In contrast, for 85% of Proctor density, the UCS values go on decreasing with increasing no of freezing-thawing cycles.
3. It is seen that the UCS value has been reduced as the degree of saturation increased. It is because at lower water content volume of voids has more portion of air instead of water, so the suction value is more at lower water content which gives additional strength to the soil.

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